

THE VOYAGER ENCOUNTERS WITH SATURN

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Abstract

Two Voyager spacecraft were launched in 1977 on a mission of exploration and scientific investigation of the outer solar system. The autonomous spacecraft carried out complex observational sequences of Jupiter and Saturn and their rings, satellites, and magnetospheres. A brief overview of some of the discoveries about the Saturnian system is presented.

Introduction

The Voyager Program was undertaken by NASA in 1972 as a major step in the exploration of the outer solar system. Objectives of the program included comparative investigations of the Jovian and Saturnian planetary systems and the study of the interplanetary medium at increasing distances from the Sun. Recently the objectives have been extended to include an investigation of Uranus and possibly Neptune. Such an ambitious program of exploration and scientific investigation is a particularly appropriate topic for the Dryden Lectureship in Research, since it requires the combined skills of many engineers and scientists in the type of cooperative effort that Hugh Dryden felt would advance both science and technology. The Voyager Project is being conducted for NASA by the Jet Propulsion Laboratory of the California Institute of Technology and involves the efforts of more than 100 scientists from university, government, and industrial laboratories.

For the 1983 Dryden Lecture, I have chosen to briefly describe the Voyager spacecraft and to provide an overview of the scientific results from the Saturn encounters.

The Spacecraft

The design of the Voyager spacecraft, which was based on experience with previous Mariner spacecraft, incorporates a number of new elements in order to achieve autonomous operation of complex sequences of scientific and engineering activities at Saturn where the round trip light time of ~3 hours severely limits control of the spacecraft from Earth. An outline of the spacecraft is shown in Figure 1.

The spacecraft is controlled by three interconnected computer systems. The attitude and articulation control subsystem (AACS) provides software control of spacecraft attitude and maneuvers and pointing of the articulated scan platform which carries two vidicon cameras, an ultraviolet spectrometer, an infrared interferometer, and a photopolarimeter. The flight data system (FDS) provides software control of the operation of the scientific

instruments and compacting and formatting of science data for the numerous telemetry modes, while the computer command subsystem (CCS) provides software control of the complex sequence of scientific and engineering activities. Each CCS program, or sequence, can control the spacecraft activities for as long as 6 months during cruise and as little as 18 hours during peak encounter periods. A single CCS program can easily generate 300,000 precisely timed commands, thus providing considerably more sequencing capability than would be possible via ground commands. In addition, the on-board computers have fault detection software which allows the spacecraft to take corrective action, such as switching to redundant subsystems, without waiting for commands from Earth. Because of the long flight time and the requirement for autonomous operation, there are redundant units for most of the engineering subsystems, including the three computer subsystems.

Several other characteristics of the Voyager design also directly affect the scientific capabilities of the spacecraft and instruments. The three-axis stabilization provides long integration times for long-exposure imaging of low contrast objects and for high resolution spectroscopy, while the X-band telemetry provides a data rate of 44.8 kilobits/s from Saturn. In addition, an S-band transmitter provides dual frequency capability for radio occultation studies of planetary atmospheres and rings. The spacecraft is powered by radioisotope thermoelectric generators (RTG) which provide more than 400W of electrical power.

There are 11 scientific investigations on the Voyager spacecraft as indicated in Table 1. The locations of the instruments are shown in Figure 1, while their nominal characteristics are indicated in Table 2. As previously noted, the four boresighted instruments (ISS, IRIS, PPS, and UVS) are mounted on a scan platform having two axes of articulation which provides complete coverage of viewing directions.

Mission Description

Two essentially identical Voyager spacecraft were launched in 1977 toward encounters with the Jovian and Saturnian planetary systems. As shown in Figure 2, Voyager 1 arrived at Jupiter on March 5, 1979, and with a gravity assist from the Jovian flyby, continued on to an encounter with Saturn on November 12, 1980. The Voyager 1 trajectory at Saturn was chosen to provide a close encounter with Titan, a planet-sized satellite with an atmosphere, and to provide an optimum geometry

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for dual-frequency radio occultation studies of Saturn's rings. In addition, the trajectory provided close approaches to three of the moderate-sized icy satellites (Mimas, Dione, and Rhea) and to a number of minor satellites.

Voyager 2 was launched on a slower trajectory, arriving at Jupiter on July 9, 1979, and continuing on to an encounter with Saturn on August 26, 1981. This late arrival date was chosen so that Saturn would be in a position which permitted a gravity-assisted continuation on to Uranus and Neptune. The exact time of arrival, however, was chosen to provide close approaches to Enceladus and Tethys and closer observations of Hyperion, Iapetus, and Phoebe than achieved by Voyager 1. The Voyager 2 trajectory also provided improved viewing of the rings and measurements in a different region of Saturn's magnetosphere.

A wide range of scientific studies of the Saturnian system were undertaken during the two encounters, including studies of the planet, the rings, the satellites, and the magnetosphere. Following are some of the highlights from these four major areas of study and a brief comment on the continuation of the Voyager mission.

The Planet

The outer planets are giant planets in comparison with Earth and the other inner planets, Mercury, Venus, and Mars. Unlike these rocky inner planets, however, Jupiter and Saturn are mainly hydrogen and helium. As a result, Saturn, which has a diameter almost 10 times that of Earth, has a density of only 0.7 g/cm^3 . Based on analysis of the gravitational effects on the Pioneer 11 flyby trajectory, it is thought that there is a small rocky core at the center of Saturn. However, the bulk of the planet is gaseous and liquid hydrogen, some helium, and traces of such compounds as ammonia which freeze into crystals at the top of the atmosphere to form the clouds which give the planet its visible form. Among the objectives of the Voyager encounters were studies of Saturn's internal heat source and of the dynamics, structure and composition of the Saturnian atmosphere.

Internal Heat Source

Infrared measurements indicate that Saturn's effective temperature is 95K, almost 13K warmer than it would be if its only source of heat was the absorption of sunlight. Thus, Saturn radiates almost twice as much heat as it absorbs from the sun, the excess heat being generated internally in the planet. In the case of Jupiter, which also radiates almost twice as much heat as it absorbs, calculations indicate that it is still cooling off from the high internal temperature generated during its formation $\sim 4.6 \times 10^9$ y ago. However, those same calculations indicate that Saturn, which is smaller, should have cooled off $\sim 2.5 \times 10^9$ y ago and, therefore, that there must be another source of energy.

Several years ago, Stevenson and Salpeter proposed that when a giant planet had sufficiently cooled, the helium in the deep

atmosphere would become immiscible in hydrogen and begin falling to the center of the planet, releasing gravitational energy in the process. Voyager measurements of the helium abundances are consistent with this model in that relative to hydrogen, there is only two-thirds as much helium in the top of Saturn's atmosphere as in the top of Jupiter's.

Dynamics

The presence of a significant internal heat source could also have a significant role in the dynamics of the atmosphere. The basic data for the dynamical studies included the determination of wind velocities from time-lapse images of cloud motions and measurements of temperature at various depths in the atmosphere.

As at Jupiter, the basic wind pattern consists of eastward and westward jet streams with large circular storm systems occurring in regions of high wind shear between jet streams of opposing directions. There are, however, several important differences between the two planets. The equatorial jet stream on Jupiter is confined to latitudes of less than $\sim 15^\circ$, while that on Saturn extends up to more than $\sim 35^\circ$. Furthermore, the maximum speed of the Saturnian equatorial wind is $\sim 500 \text{ m/s}$ ($\sim 1100 \text{ mph}$), almost five times faster than on Jupiter. At higher latitudes, the jet streams are alternately eastward and westward with increasing latitude, with a marked degree of similarity in the latitude dependence of the winds in the northern and southern hemispheres.

Further consideration of these results indicates that the Saturnian wind pattern extends at least several thousand kilometers down into the atmosphere, and the similarity of the winds in the two hemispheres has led to the suggestion that the wind pattern may extend so deeply that it emerges at the same latitudes in the opposite hemisphere. The applicability of either this deep flow model or a more conventional thin-layer model are being theoretically investigated and debated.

The Rings

Rings are composed of large numbers of relatively small particles orbiting a planet. The individual particle motions, and hence the rings, are controlled by gravitational forces and collisions, with electromagnetic effects also of some importance for the smallest particles. The dynamical properties of planetary rings are closely related to those of larger rotating disks of matter such as that out of which the solar system formed and the disks of gas, dust, and stars which comprise spiral galaxies.

Three planets are known to have rings, although the Saturnian ring system is much more extensive than those of Uranus and Jupiter, both of which were discovered only in the last six years. From Earth, Saturn's ring system appears to be organized into three major sections. The outermost region, the A-ring, is separated from the broader, brighter B-ring by the Cassini Division, discovered in 1676. Interior to the B-ring is a diffuse C-ring which is more

difficult to observe from Earth. Just outside of the A-ring lies the F-ring, a narrow ribbon of particles discovered by Pioneer 11 in 1979. The surfaces of the particles in the A and B-rings have the spectral properties of water ice and it is likely that the ring particles are mainly water ice. The Voyager observations of Saturn's rings have contributed significantly to both the conceptual and detailed understanding of structure, dynamics, and particle size distributions of this major ring system, especially with respect to the role of Saturn's inner satellites in determining the structure and dynamics of the rings.

The F-Ring

Because of repetitive collisions between ring particles, narrow rings such as the F-ring will rapidly diffuse away unless there are constraining forces. When narrow rings were discovered around Uranus in 1977 by Elliot and his coworkers, Goldreich and Tremaine proposed that such narrow rings could be maintained by the "shepherding" action of small satellites inside and outside of each ring. Such a pair of shepherding satellites has been found in the Voyager images, allowing detailed studies of the shepherding process.

The Cassini Division

While small satellites can constrain small rings such as the F-ring, constraining the outward diffusion of particles in the massive B-ring requires the gravitational interaction of much larger, more massive satellites. However, systematic energy exchange between ring particles and a satellite occurs only for particles with orbital periods which are in resonance with that of the satellite. Thus, the Cassini Division occurs at the radial location where the orbital period of a particle would be exactly one-half that of Mimas, the innermost of the moderate-sized Saturnian satellites. Because of the resonant gravitational interaction with Mimas, particles are perturbed from their circular orbits and a gap between the A and B-rings is created. Thus, the resonant interaction is a barrier which defines the outer edge of the B-ring, effectively preventing further outward radial diffusion of B-ring particles. A similar resonance barrier occurs at the outer edge of the A-ring due to the presence of two smaller satellites.

Density Waves

At other resonance locations in the rings, the gravitational perturbations are too small to clear a gap or form a barrier. However, the particle orbits are disturbed in a systematic manner which results in localized regions of increased particle density. As the perturbing satellite orbits Saturn and the induced density enhancement propagates radially outward from the resonant radius, a spiral density wave is generated. In one sense, these waves can be regarded as trailing wakes generated by the gravitational resonant perturbations induced by satellites orbiting external to the rings. More than 20 such wakes have been identified in the

Voyager data from the photopolarimeter, the ultraviolet spectrometer, and the imaging system.

The amplitude and spacing of the waves are diagnostic of the velocity of the particles and the mass of particles per unit area of ring surface. For example, in one region of the B-ring, this analysis indicates that the average mass per unit area is $\sim 70 \text{ g/cm}^2$, while in regions of the A-ring, a somewhat smaller mass of $\sim 50 \text{ g/cm}^2$ appears typical. Assuming these values are representative of the entire A and B-rings, the total mass of Saturn's ring system is about the same as that of the satellite Mimas.

Particle Sizes

Several different Voyager observations provided information on a broad range of particle sizes in the rings. Observations of the attenuation of starlight by the photopolarimeter and the ultraviolet spectrometer during stellar occultation provided measurements of the opacity of the rings due to particles with radii down to ≤ 1 micron. Images of the sunlight transmitted through to the dark side of the rings gave similar information.

The optical data can be compared with measurements of the attenuation and scattering of the dual-frequency signals from the spacecraft as it passed behind the rings. With wavelengths of 3.6 and 13 cm, the radio occultation results provided a measure of the number of particles with radii greater than 1 and 4 cm, respectively, while observations of the forward diffraction pattern of the scattered radio waves provided an indication of the number of meter-sized particles. Although the analysis has been completed for only a few discrete regions, it appears that the bulk of the mass of the rings is due to particles with 2 to 6 m radii, with relatively few particles having larger radii.

Although contributing little to the mass of the rings, there are many smaller particles. In the C-ring, for example, only $\sim 1/3$ of the radio opacity, which is proportional to the cross sectional area and number of particles, is due to meter-sized objects. Similar fractions are due to particles with $1 \leq r \leq 4$ cm and with $4 \leq r \leq 100$ cm. In contrast, in the Cassini Division there are relatively few particles with $r \leq 4$ cm and $2/3$ of the opacity is due to meter-sized objects. Thus, there are distinct differences in the distributions of particle sizes for the various regions in the rings, differences which may be related to the origin and dynamical evolution of the ring system.

Ring Thickness

The thickness of the rings is closely related to other dynamical properties of the rings. From ground-based observations it was known that the A- and B-rings are less than a few kilometers thick. The stellar and radio occultations provided an opportunity for refining the thickness measurements, at least at the edges of gaps and divisions where the abruptness of the onset of attenuation is an

indication of the thickness of the ring edges. Generally, it was found that the transitions in attenuation were so abrupt that only an upper limit of ≤ 200 m could be established. Other considerations suggest that the rings are likely only 20 to 50 m thick, which would indicate that the relative velocities of colliding ring particles is ≤ 1 mm/s.

Spokes

Dark patches were observed in the B-ring when Voyager 1 was approaching Saturn. Since the particles in the dark patches, like all other ring material, are in orbit about Saturn, the patches appeared to rotate like spokes in a wheel. Unlike real spokes, however, the patches are not solid objects but transient changes in the local reflectivity of the B-ring, perhaps resulting from the formation of a layer of small, micron-sized particles just above the larger particles comprising the B-ring. Because spoke particles near Saturn orbit more quickly than those further away, an individual spoke is quickly dispersed. Thus, the spokes must be continually recreated by some as yet unknown process.

There are several indications that electromagnetic forces may be important for spoke dynamics, as would be the case if the spoke particles are sufficiently small and electrically charged. It is observed that the spokes form along a radial line corotating with Saturn's magnetic field. It is also observed that spokes are more likely to form several hours after a particular longitude in the magnetic field emerges from behind Saturn as the planet rotates. However, there is no currently accepted theoretical explanation for the spoke-like features.

Saturn Electrostatic Discharges (SED)

Another puzzling phenomena which may be the result of electromagnetic effects in the rings are short bursts of broadband radio emission. Individual SED bursts last tens of milliseconds and occur in episodes of several hours duration. The episodes recur every 610 m, a period which is significantly different than Saturn's period of rotation which is 639.4 m. Because of the high speed jet stream, the equatorial atmosphere has a period similar to that of the SED episodes, leading to the suggestion that the bursts originate in atmospheric lightning discharges. However, the spectral and energy content of the bursts and the fact that none were detected at Jupiter where lightning was observed leads others to conclude that the discharges are not due to atmospheric lightning, but may originate in the rings at the radial location where the orbital period is 610 m. However, there is currently no accepted theoretical model for the generation of such discharges by particles in the rings.

Satellites

Voyager 1 and 2 returned images of 17 satellites and detected the presence of several other smaller ones as unresolved points. The only major satellite, Titan, is almost exactly the same size as the planet Mercury but is half

water ice and only one third as massive. Eight others are intermediate in size, with diameters ranging from ~400 to ~1500 km and densities of only ~1.1 to ~1.4 g/cm³. All of these intermediate satellites must therefore contain less rock than ice, and Iapetus, which has the lowest density, may contain substantial quantities of ammonia ice and hydrocarbons. The marked abundances of various ices in the Saturnian satellites are an indication of the low temperatures which prevailed in the outer regions of the solar system during its formation.

The remaining Saturnian satellites are minor satellites of irregular shape with maximum dimensions of ≤ 200 km. The two F-ring shepherd satellites are minor satellites as are satellites 1980S1 and 1980S3 which share essentially the same orbit. Other minor satellites share orbits with the moderate-sized satellites Tethys and Dione. The profusion of minor satellites has led to the suggestion that they are fragments of larger bodies which were disrupted during a period of heavy bombardment by asteroidal fragments or comet nuclei early in the formation of the solar system. The minor satellite Phoebe is an exception, however, since it is in a retrograde orbit and is likely a captured asteroid. Its roughly spherical surface is very dark and reddish, consistent with the properties of a class of asteroids believed to be very primitive and unmodified.

Although further detailed studies of each of the satellites will contribute to an overall understanding of the Saturn system, several have such unique characteristics that they have already received additional attention. One of these is the moderate-sized satellite Enceladus and another is Titan, the only satellite in the solar system known to have a substantial atmosphere.

Enceladus

Because the moderate-sized satellites are small and contain relatively little rock and the associated radioactive elements which produce heat, it was possible that these satellites would show little evidence of thermally driven tectonic activity. However, most of the moderate-sized satellites show evidence of such activity, although Enceladus, with a diameter of only 500 km, has by far the most active surface. At least five distinct surface units have been identified on Enceladus, with the youngest, least cratered area possibly being created as recently as several hundred million years ago. Other evidence for tectonic activity on Enceladus includes a rectilinear pattern of faults, possibly the result of surface expansion, and ridged plains similar to those observed on the Jovian satellite Ganymede, which is almost 2000 times more massive.

Because Enceladus is so small, it seems highly unlikely that radioactive heating could be responsible for the extended duration of thermal activity. A more likely source of thermal energy is tidal dissipation similar to that which melts the interior of the Jovian satellite Io and drives its vigorous volcanic activity. However, theoretical estimates of the

amount of tidal heating implied by the current eccentricity of Enceladus' orbit are too low to account for the degree of observed tectonic activity. Perhaps Enceladus was in a much more eccentric orbit when the ice magma flooded the surface, erasing the record of earlier meteoritic collisions. This and other possible explanations are presently being pursued.

Titan

Investigations of this planet-sized satellite and its substantial atmosphere were key objectives of the Voyager mission. The Voyager 1 trajectory was chosen to pass within ~4000 km of Titan's surface, although opaque atmospheric hazes prevented observations of the surface. The trajectory also provided for radio occultation studies of the altitude dependence of the temperature and pressure of the atmosphere, for studies of the interaction of Titan with the Saturnian magnetosphere, and for infrared and ultraviolet studies of atmospheric composition. Voyager 2 provided additional studies of the light scattering properties of the haze particles.

These studies indicate that Titan's atmosphere contains about 80% nitrogen and has a surface pressure of ~1.5 bars, not much different than the Earth's atmosphere. Instead of oxygen, however, Titan's atmosphere contains up to 6% methane and may contain substantial quantities of argon. At a surface temperature of 95K, methane is near its triple point and likely behaves much as water on Earth. That is, there may be lakes or oceans of liquid methane which continually supply methane gas to the atmosphere. As the methane rises in the atmosphere and cools, it would freeze, forming clouds of methane ice a few kilometers above the surface.

In the upper atmosphere, the methane undergoes photochemical reactions which produce organic molecules such as acetylene, ethylene, ethane, hydrogen cyanide, and many others which have been spectroscopically identified. Thus, the hazes in Titan's atmosphere are hydrocarbons rather than oxides as in the Earth's case. Since the hydrocarbon photochemistry currently occurring in Titan's atmosphere may resemble that which occurred in the Earth's early atmosphere, there is considerable interest in further studies of this planet-sized satellite.

The Magnetosphere

Magnetic fields are generated by the motions of electrically-conducting fluids deep within planetary interiors. For the giant planets which are mainly hydrogen and helium, calculations suggest that at pressures greater than several million atmospheres, hydrogen becomes an electrical conductor and is the source of the external magnetic field. The dipole field extends large distances from the giant planets, until it becomes too weak to balance the pressure of the impinging solar wind. Saturn's magnetic field usually extends beyond Titan's orbit, more than 10^6 km from Saturn.

Since the magnetic field is generated within the planet, it will corotate with the interior. Well before the Voyager 1 encounter, periodic kilometric radio emissions from particles spiraling along Saturn's magnetic field indicated that the field was rotating with a period of $10^h 39.4^m$, thus providing the first measurement of the period of rotation of Saturn's interior. Subsequent observations and analysis revealed that the Saturn Kilometric Radiation (SKR) emanates from the auroral zone at 80°N and occurs preferentially when a particular Saturnian longitude faces the Sun. Strong ultraviolet auroral emissions from this longitude were also observed. It is also interesting that the ring spokes are most likely to occur at the same preferred longitude. However, measurements of the magnetic field failed to identify any asymmetry which could account for the increased occurrence of auroral SKR or spoke activity at any preferred longitude.

As the magnetic field corotates with Saturn, it carries with it plasma ions and electrons. Thus a source of plasma such as the icy surfaces of the inner satellites or the atmosphere of Titan rapidly creates a plasma torus surrounding Saturn. Inside of ~6 Saturn radii (R_s), there is a torus of hydrogen and oxygen ions, probably resulting from the sputtering of water ice from the surface of the two moderate-sized satellites Dione and Tethys. Beyond the inner torus there is a thick sheet of plasma extending out to ~17 R_s . The presence of energetic molecular ions strongly suggests that some of the plasma in the outer regions originates in Saturn's ionosphere.

Titan's atmosphere is also a source of hydrogen and nitrogen in the outer magnetosphere. As the magnetic field corotates past Titan at ~200 km/s, the magnetospheric plasma is deflected around the satellite, forming a wake. During this interaction, the plasma picks up ions from the top of Titan's atmosphere and carries them away to become part of the trapped plasma in the outer magnetosphere. Neutral hydrogen also escapes from Titan's atmosphere, forming a diffuse neutral torus between ~8 and ~25 R_s . As the hydrogen atoms become ionized, they too become part of the magnetospheric plasma corotating with Saturn's magnetic field.

The Heliosphere, Uranus, and Neptune

After their encounters with Saturn, both Voyagers continued their journeys outward in the solar system. During their interplanetary cruise, many of the instruments will be observing the supersonic solar wind plasma which streams radially away from the sun, carrying with it the solar magnetic field and forming the heliosphere. Other instruments will be searching for particles accelerated by the solar wind and for cosmic rays from nearby regions in the galaxy which are of such low energy that the outward streaming solar wind limits their penetration to the outer fringes of the solar system.

With increasing distance from the sun, the solar wind becomes increasingly tenuous and at some distance will no longer be able to withstand the pressure of the surrounding interstellar medium. The distance to the heliospheric boundary is unknown, but may be 30 to 60 AU from the Sun (Earth is at 1 AU, Neptune at ~30 AU). In 1990, Voyager 1 will be at 40 AU, traveling outward at ~3.5 AU/y. Perhaps during the next decade, Voyager 1 will discover the heliospheric boundary and continue its journey beyond.

During this same period, Voyager 2 will be encountering Uranus and Neptune. The Uranus encounter observations will begin in late 1985, with closest approach on January 24, 1986. The Uranus flyby trajectory has been chosen to send Voyager 2 off in the direction of Neptune, where it will arrive on August 24, 1989. Even less is known of Uranus and Neptune than was known about Saturn before the Voyager encounters. Thus, assuming the two spacecraft will continue to function well into the future, further discoveries await their continued journey into the outer solar system.

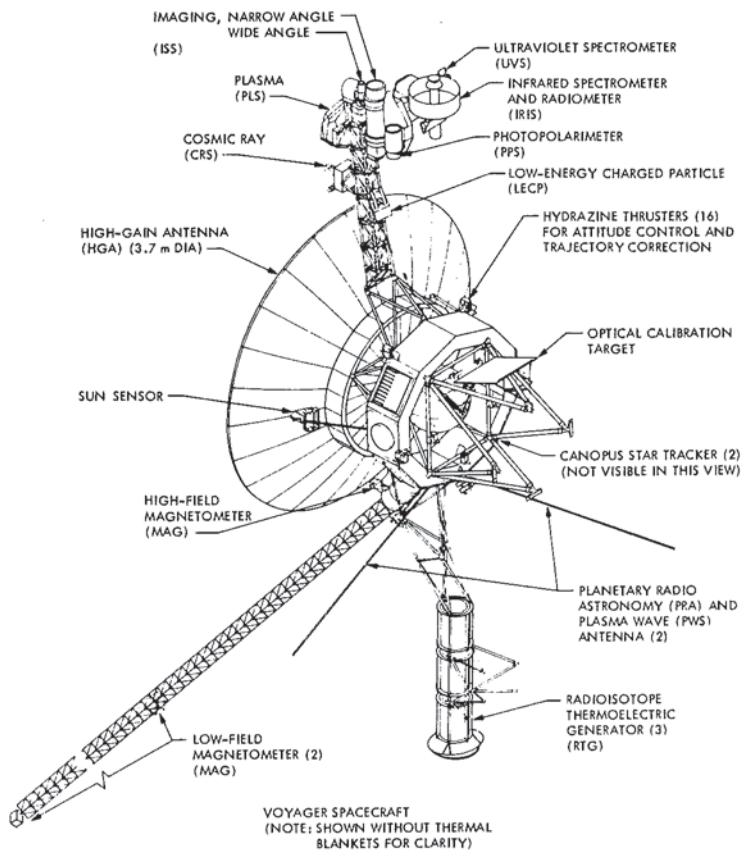


Figure 1. A drawing of the Voyager spacecraft showing the location of the science instruments. The Radio Science Investigation uses the dual-frequency spacecraft transmitters, an Ultra Stable Oscillator, and the 3.7 m high-gain antenna.

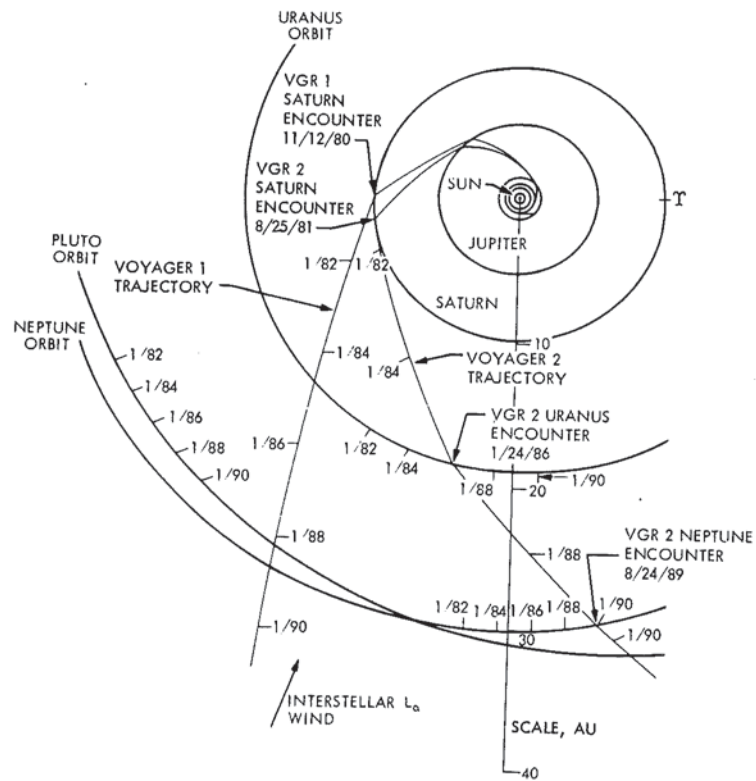


Figure 2. View from normal to the ecliptic plane of the Voyager 1 and 2 trajectories.

Table 1. Voyager Science Investigations

Investigation Area	Principal Investigator/Institution
Imaging Science (ISS)	Smith/Univ. Arizona (Team Leader)
Infrared Spectroscopy and Radiometry (IRIS)	Hanel/GSFC
Photopolarimetry (PPS)	Lane/JPL
Ultraviolet Spectroscopy (UVS)	Broadfoot/Univ. So. California
Radio Science (RSS)	Tyler/Stanford Univ. (Team Leader)
Magnetic Fields (MAG)	Ness/GSFC
Plasma (PLA)	Bridge/MIT
Plasma Wave (PWS)	Scarf/TRW
Planetary Radio Astronomy (PRA)	Warwick/Radiophysics, Inc.
Low Energy Charged Particles (LECP)	Krimigis/JHU/APL
Cosmic Rays (CRS)	Vogt/Caltech

Table 2. Instrument Characteristics

Investigation	Nominal Characteristics
ISS	Two Se-S vidicon cameras ($f=1500$ mm and $f=200$ mm); Narrow-angle camera; $19 \mu\text{rad/line pair}$, $2900 - 6400 \text{ \AA}$
IRIS	Michelson interferometer ($3.3 - 50 \mu\text{m}$) and radiometer ($0.33 - 2 \mu\text{m}$); 51 cm telescope; 0.25° FOV
PPS	Photomultiplier with 15 cm telescope; $2630 - 7500 \text{ \AA}$; 3.5° , 1° , $1/4^\circ$, $1/10^\circ$ FOV; 2 linear polarizers
UVS	Grating spectrometer; $500 - 1700 \text{ \AA}$ with 10 \AA resolution; airglow ($1^\circ \times 0.1^\circ$ FOV) and occultation ($1^\circ \times 0.3^\circ$ FOV)
RSS	S-Band (2.3 GHz) and X-Band (8.4 GHz); Ultra Stable Oscillator ($<4 \times 10^{-12}$ short-term drift)
MAG	Two low-field ($<10^{-6} - 0.5$ G) and two high-field ($5 \times 10^{-4} - 20$ G) magnetometers; 13 m boom; $0 - 16.7$ Hz
PLS	Earth-pointing sensor (10 eV - 6 keV ions) and lateral sensor (10 eV - 6 keV ions, 4 eV - 6 keV electrons)
PWS	Sixteen channels (10 Hz - 56.2 kHz); waveform analyzer (150 Hz - 10 kHz); share PRA antennas
PRA	Stepping receiver (1.2 kHz and 20.4 kHz - 40.5 MHz); right and left circular polarization; orthogonal 10 m monopole antennas
LECP	Two solid-state detector systems on rotating platform; 10 keV - 10 MeV electrons; 10 keV/nuc - 150 MeV/nuc ions
CRS	Multiple solid-state detector telescopes; $3 - 110$ MeV electrons; $\sim 1 - 500$ MeV/nuc nuclei; 3-dimensional anisotropies